Chapter 18

Nonionizing Radiation

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The significance of electric fields, magnetic fields, and electromagnetic fields, all physical factors that can affect job performance, continues to increase in the human-machine interface. All astrophysical objects in the universe are thought to have magnetic fields[1] (MF), which can range from very small fields, one-millionth the intensity of that of Earth, to those of white dwarf stars (~10 kT) and neutron stars (1000 MT). Future new technologies undoubtedly will lead to the development of new instruments and devices that emit electromagnetic radiation (EMR) of as-yet unknown temporal and spatial configurations. Probably such EMR will be put to use in future space technology, as was the case for the Forecast-2 project to improve aerospace technology, satellite-mounted solar-energy transformers, and satellite communications and tracking systems, all of which operate on frequencies ranging from 200 MHz to 14 GHz.[3–5]

Exposure to unaccustomed field gradients and intensities poses concerns for space operations. The electromagnetic environment aboard a space vehicle (including that experienced during extravehicular activities) is determined by the contributions of electric fields (EF), MF, and EMR from on-board sources and extremely-low-frequency variations in the EMR from the motion of the spacecraft within the low-Earth-orbit geomagnetic field. During deep-space travel to other planets, crew members will have to spend long periods in hypomagnetic conditions, and will be exposed to ultraviolet radiation (UVR) from the sun as well. (Some Russian investigators have even used UVR-band EMR to improve physiological status during or after flights.) These forms of energy are unlikely to be dangerous to crews in low-Earth orbit under routine flight conditions. However, the duration and constancy of exposure to factors that will manifest variable characteristics over time, and are generated within a closed, metal-walled space, should be borne in mind. Moreover, EMR could modify physiological reactions to other flight factors such as weightlessness, hypokinesia, or ionizing radiation, and these factors in turn could affect an individual's sensitivity to EMR.

From a practical standpoint, existing standards for occupational exposure to EMR should be assessed for their applicability to space crews during flight. Many fundamental improvements have been made in electromagnetobiology, particularly with regard to EMR dosimetry, since the previous edition of this work *(Foundations of Space Biology and Medicine)* was published in 1975. As a result, radiation exposure standards and measurement instruments have been updated. However, many biological phenomena associated with weak EMR, especially in humans, have yet to be explained satisfactorily. Human reactions to UVR also vary greatly among individuals.

This chapter focuses on data published between 1975 and 1990 regarding the biological effects of EF, MF, EMR, and UVR. Our own opinions regarding the biological effects of nonionizing radiation are similar to the conclusions of the International Nonionizing Radiation Committee of the International Radiation Protection Association (IRPA/INIRC)[2,6] and the World Health Organization (WHO).[8] Technical aspects of dosimetry and related topics are reviewed in detail elsewhere.[7–13] The effects of EMR in combination with other aspects of the spaceflight environment are considered in Chapter 21 of this volume. With regard to the present chapter, topics are presented in the order described below.

The development of new sources of energy, means of storing and transmitting energy for long distances, extremely long-distance communications, and related issues in occupational safety have prompted both epidemiological observations and experimental investigations of extremely-low-frequency EMR and geomagnetic fields. The increasing numbers of video display terminals in use have generated concern regarding the potential risk to computer operators from EMR. The magnetobiology of weak EMR is fraught with controversy, with many points of view expressed regarding the mechanisms by which natural EMR interacts with biological tissues, which of course have their own endogenous electric fields and currents.[2] Many of the biological phenomena associated with weak EMR have yet to be explained satisfactorily by physical or chemical laws. The EMR of living things is of interest not only for the potential of obtaining additional information about the vital processes of operators and systems, but also about informational interactions among living systems (including humans). Finally, the biological effects of solar UVR, which poses several potential risks to space crews, are reviewed as well.

I. General Definitions of Quantities and Units

The segments of the electromagnetic spectrum are shown in Table 1. Aspects of this spectrum discussed in this chapter

Table 1 Radiofrequency, microwave, and optical segments of the electromagnetic spectrum

Region	Frequencies	Wavelengths
Radiofrequency		
Extremely low frequency	3 to 30 Hz	100 to 10 Mm
Superlow frequency	30 to 300 Hz	10 to 1 Mm
Ultralow frequency	300 Hz to 3 kHz	1 Mm to 100 km
Very low frequency	3 to 30 kHz	100 to 10 km
Low frequency	30 to 300 kHz	10 to 1 km
Medium frequency	300 kHz to 3 MHz	1 km to 100 m
High frequency	3 to 30 MHz	100 m to 10 m
Very high frequency	30 to 300 MHz	10 m to 1 m
Ultrahigh frequency[a]	300 MHz to 3 GHz	1 m to 100 mm
Superhigh frequency[a]	3 to 30 GHz	100 mm to 10 mm
Extremely high frequency[a]	30 to 300 GHz	10 mm to 1 mm
Infrared	30 GHz to 400 THz	1 mm to 760 nm
Micrometer waves[b]	300 GHz to 30 THz	1 mm to 10 μm
Visible light	400 THz to 750 THz	760 nm to 400 nm
Ultraviolet light	750 THz to 3 PHz	400 nm to 100 nm

[a]microwave frequencies; [b]also considered to be within the radiofrequency range

include, in the radiofrequency range, 3 Hz to 300 GHz, and the ultraviolet light range (750 THz–3 PHz). The 300 MHz to 300 GHz part of the radiofrequency range also is referred to as microwave radiation.

Exposure limits formulated for frequencies of 10 MHz and above are expressed in terms of specific absorption rate (SAR), which is the power absorbed by an object in an electromagnetic field per unit mass (W/kg). The SAR can be averaged spatially over the total mass of an exposed body or its parts, or can be averaged temporally over a given exposure period or over a single pulse or modulation period of the radiation. Exposure limits also can be expressed in the "body-absent" condition in terms of power density (energy flux density), in W/m^2 (Ref. 6).

For frequencies below 10 MHz, the SAR concept is of limited value because the biological effects resulting from human exposures to these frequencies are more fundamentally correlated with the current density generated in the body. Moreover, the relationships between electric and magnetic fields outside the body and the biologically effective tissue field strengths or current tissue density have not been well developed for frequencies between 0.1 and 10 MHz. Thus, below 10 MHz, exposure limits are expressed in terms of incident (outside the body), effective electric field strength (in V/m), and effective magnetic field strength (in A/m).[6] Magnetic flux density (the force exerted on a charge moving in the magnetic field) also is used to describe magnetic fields associated with biological effects. Exposure limits generally are expressed as the root-mean-square of the magnetic flux density, in tesla (T) or V-sec/m^2 (Ref. 2).

Because the electric fields and currents produced by biological systems are extremely small compared to the electric and magnetic fields produced by transmission lines and electrical devices, the electric and magnetic fields interact separately with biological systems and must be considered separately from one another. Electric and magnetic field strengths, as noted above, are expressed in V/m or A/m, respectively. Biological effects of magnetic fields should be related to the field on the surface of the body as well as to the electric fields, currents (in amperes, A), and current densities (A/m^2) induced inside the body.[2]

II. Biological Consequences of Exposure to Nonionizing Radiation

Epidemiologic evaluation of the consequences of exposure to electromagnetic fields is complicated by several factors, including the scarcity of high-quality dosimetry and the complexity of isolating and identifying environmental factors as having caused a disease or condition. Genetic effects such as cancer can develop many years after exposure, further complicating efforts to establish causal connections. Finally, social reactions to technological factors can distort epidemiological research and remediation efforts. A review of recent epidemiologic reports concerning the biological effects of radiofrequency EMR is presented below. Our focus on the neurophysiologic, hematologic, and visual systems, and on long-term effects, reflects the importance of these issues with regard to occupational health, whether for Earth populations or space crews.

A. Radio- and Microwave Frequencies

1. Neurophysiological Effects

Exposing animals briefly to microwave radiation produces neurophysiological reactions that correlate closely with thermal effects. The behavioral reactions that precede overt neurophysiological symptoms occur at nearly lethal amounts (> 4 W/kg). Although much data have been collected, evidence of neurophysiological reactions to power densities less than 1 mW/cm^2 (i.e., < 1 W/kg for mice and rats) cannot be considered reliable. Parallel investigations in the U.S. and U.S.S.R. found no evidence of behavioral disruptions in rats irradiated at 10 mW/cm^2 (2.45 GHz) for 7 hours; U.S. (but not Soviet) investigators noted a decrease in Na^+-K^+-ATPase activity in the CNS.[14] Although much has been learned regarding the psychophysiological effects of radiofrequency EMR in animals, much also remains unclear with regard to prolonged or repeated exposures.

Humans can hear rectangular, pulsed exposure to microwave energy ranging from 200 MHz to 3 GHz.[15] The duration and frequency of repetitive impulses determine whether the sound is perceived as a click or a chirp. Pulsed EM energy induces a thermoelastic pressure wave (threshold absorption of energy in an impulse of 16 mJ/kg)[16] in tissues of the brain, which stimulates inner-ear receptors through bone conductivity. These studies suggest that biological effects at a mean power density below 1 mW/cm^2 (with peaks to 300 mW/cm^2) can be present in humans. The significance of this phenomenon remains unclear.

Individuals who work with EMR of power density less than 1 mW/cm^2 have shown evidence of increased anxiety and depression, as well as complaints of loss of memory, malaise, and decreased perceptual thresholds.[17–19] On the other hand, no deviations in the health of military radar operators were found in another group that underwent psychophysiological evaluations.[20] Yet another group of 500 radar-station operators, irradiated at power densities no greater than 5 mW/cm^2 for 2 hours a day for 15 years, had no greater prevalence of neurasthenia or neurosis during this period than did a control group.[21] One of two human subjects accidentally subjected to radiation of high power density (up to 16 W/cm^2) noted sensations of warmth in the neck and head similar to that caused by direct sunlight. Both individuals experienced nausea, dizziness, anxiety, poor appetite, and increases in blood pressure and sensitivity to light. No visual disturbances were noted.[22] Personality changes and neurological symptoms have been reported in individuals subjected to radiation at power densities exceeding U.S. standards.[23] However, these reports may have involved overestimations of the harm caused by exposure to electromagnetic energy.

2. Hematologic and Immune Effects

Several investigators[24–27] have concluded that the chronic effects of exposure to microwaves of power density less than 2 mW/cm^2 may include unstable changes in the hematopoietic system, with leukopenia more frequent than leukocytosis or increased numbers of lymphocytes. Monocytosis, pathological granularity of neutrophils, reticulocytosis, and thrombocytopenia also have been reported, although detailed analyses have shown that these changes are statistically insignificant, even during brief exposures that involve heat perception. Moreover, changes such as these are characteristic of many other adverse working conditions as well.[28] Yugoslavian investigators[21] found no significant hematopoietic changes in a group of people who had worked with radar for 15 years.

The increase in death from diseases, including those arising from the hemopoietic system, was no greater than 0.017% in a group of military operators, radar-station workers, and technicians working with other radioelectronic equipment.[29,30] According to WHO data, this increase does not exceed the mean statistical incidence of diseases for men in that age range. Results from a 19-year longitudinal study revealed that the death rate from cancer in populated regions including military air bases was no different from that of regions without such bases.[31]

Our own analyses of the effects of microwaves on immune reactions[25–27,32] have led us to conclude that immunological reactions occur at specific absorption rates (SAR) of 0.4 W/kg and higher, with the clearest and most persistent changes being associated with thermal reactions. The qualitative characteristics of immunological reactions (e.g., lymphocyte migration) in many respects are similar to the response to steroid hormones; continuing exposure to EMR leads to physiological adaptation or attenuation of the immunological reactions. However, in vivo effects cannot be reproduced by irradiating lymphocyte cultures in vitro. In vitro immune responses to microwaves resemble reactions to high temperature, although several unique features are associated with the rate of accumulation and distribution of heat in the body.

3. Cataracts

Cataractogenesis is one of the most thoroughly studied reactions to ionizing and ultraviolet radiation. Nevertheless, extrapolating results obtained from animals to humans is complicated by differences in head size and eye positions among species.[33] Other complications deserving of consideration are frequency and refraction. For example, the distribution of thermal effects from microwaves in the eyes with regard to frequency depends on the resonance of the eyes and the head. At frequencies below 1.5 GHz, ocular dimensions are too small for concentrating the field, and thus the effects will be determined by the resonance of the whole head. At frequencies above 1.5 GHz, resonant heat peaks are possible in the eyes. Also to be considered are refraction effects, a model of which for the frequency range 1–35 GHz is described in Ref. 34.

The consistency and reliability with which cataracts can be produced in animals have inspired searches for signs of cataracts in humans working with radiofrequency radiation sources. Radiofrequency EMR has been ranked fifth among risk fac-

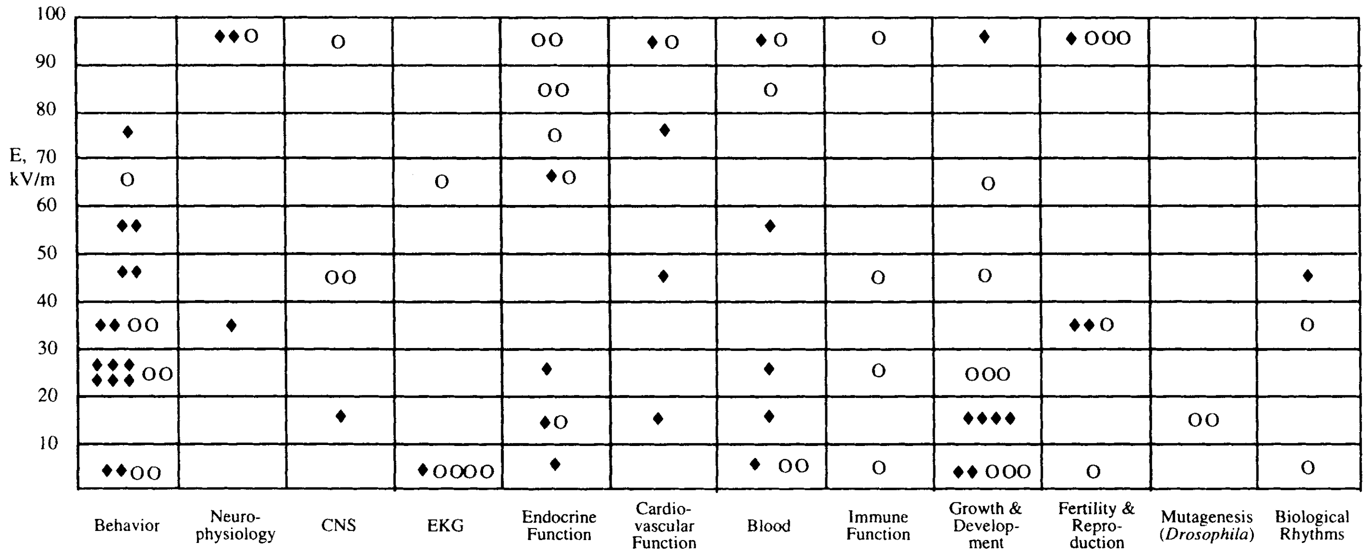

Fig. 1 Biological effects of 50- to 60 Hz electric fields on animals. Each symbol represents results from one experiment involving chicks, rats, guinea pigs, or monkeys (except as noted otherwise). Solid diamond, effect found; open circle, no effect found. Adapted from Ref. 48.

tors for cataracts, after diabetes, solar UVR, metabolic disorders (e.g., galactosemia, hypothyroidism, hypercalciemia), and ionizing radiation.[35] Unfortunately, published information often does not contain the requisite details of the electromagnetic situation, subject age, dosimetry, or frequency. Thus, determining whether the population under study actually has been exposed to microwave irradiation often is difficult. As noted above, thermal effects are thought to be responsible for electromagnetic cataracts in humans. According to one study, if occupational exposure produces cataracts at all, it does so only if the power density is at least 90 mW/cm^2 (Ref. 25). In another study, 4000 subjects who were exposed in the workplace to microwaves of power density less than 10 mW/cm^2 were examined for clinical evidence of eye damage (including cataracts). No evidence of eye damage was found.[36] (These results do not eliminate the possibility of ocular damage at higher exposures, however.)

4. Aging, Teratogenesis, and Genetic Effects

The possibility that occupational factors might have aging, teratogenic, or genetic effects naturally raises intense scrutiny from the public. However, from a biomedical standpoint, these phenomena always are complex, and investigating the effects of EMR demands great caution on the part of investigators, particularly in detecting effects that may be hidden in uncontrolled population variance.

Three parameters can be considered reliable in evaluations of aging: total life span, weight, and the appearance of malignant tumors. Neither shortened lifespan nor increased tumor incidence were present in animals irradiated at up to 100 mW/cm^2, even after preliminary gamma irradiation.[24,37] Rather, microwave irradiation in these experiments was associated with a nonsignificant decrease in tumor formation.

Studies of teratogenesis, a significant component of any evaluation of health effects, demand strict objectivity, accurate procedures, and caution in extrapolating experimental data to humans. The unfortunate—and disproven[38]—report that exposure to microwave radiation can cause Down syndrome illustrates the need for caution in publicizing untested and uncorroborated data. The effects of EMR on fetuses are reviewed in detail in Ref. 39. Longitudinal observations of pregnant women working with microwave devices have provided no proof of teratogenic or embryotoxic effects; in fact, in one study, women subjected to high-frequency heat to alleviate pain during labor bore normal children.[40] Nonetheless, pregnant women should avoid exposing the fetus to excessive heat, whether produced by microwave radiation or some other means, since specific absorption rates greater than 20 W/kg have had teratogenic effects on animals.

We used the large number of studies reported in Ref. 24 to derive a logarithmic function that linked damage to the spermatogenic epithelium in animals to the intensity and duration of microwave irradiation. Data on mutagenic effects are contradictory, but tend to support the contention[24] that microwaves do not induce mutagenesis nor influence growth or development, at least in animals.

B. Low to Extremely Low Frequencies

Static and extremely-low-frequency (ELF) electric and magnetic fields, and their associated currents, play important roles in many biological functions. The surface of any living thing is a mosaic of weak electric potentials created by the electric activity of muscles, heart, brain, and nerves, and forms a field with frequencies ranging from 10^{-2} to 10^{-7} Hz.[41,42] Human MF range from 10^{-13} to 10^{-9} T between 0 and 2000 Hz.[43] Normal brain rhythms observed by electroencephalograms and magnetoencephalograms generally are below 20 Hz. The activity of the nervous system, in which neurons propagate direct current pulses along paths of various lengths, creates electrical signals that affect muscle or gland function. Bone growth and the regeneration of bone after injury are associated with static (and perhaps alternating) currents. Cell membranes are associated with intense electrical fields (10^4 kV/m) because of the potential difference maintained between the inside and the outside of the cell.

The possibility that human tissues may be sensitive to environmental ELF EMF has been the subject of much speculation. Reports of adverse effects demonstrated by people working with low-frequency electromagnetic fields (3 Hz–300 kHz), or living close to electric transmission lines, has led to extensive experimentation with animals as well as epidemiological observations.[8,44–47] A large-scale review of the biological effects of superlow-frequency (50–60 Hz) electric fields on animals has shown the number of positive effects to approximate the number of negative effects (Fig. 1).[48] However, the range of effects of ELF radiation on biological subjects is quite broad, and results often have been contradictory.

1. Neurophysiological and Cardiovascular Effects

Extracellular electric fields are significantly smaller than membrane fields,[49,50] which may explain why some tissues are particularly sensitive to external low-frequency EF. According to the International Nonionizing Radiation Committee of the International Radiation Protection Association (IRPA/INIRC), endogenous current densities in the body typically are about 10 mA/m^2, although they can be much higher during certain functions.[2] Current density of approximately 1 mA/cm^2, corresponding to membrane potentials of some mV, seems to be the threshold for excitation of quiescent axons,[51] although some spontaneously firing "pacemaker" neurons can be affected by current densities as small as 1 μA/cm^2 (Ref. 52). Electrostimulation of contractile tissue (e.g., muscle) also demands current densities in the mA/cm^2 range.[51]

An extracellular field produced by an external EF has been considered safe by at least one author[45] if the magnitude of that field does not exceed the EF of the living tissue. However, others maintain that the presence of continuous neural firing activity in the brain and heart makes it possible that some neurons would be influenced by current densities well below the 1 mA/cm^2 threshold needed to excite totally silent cells.[52] Indeed, cultured brain tissue has been shown to release calcium at a frequency of 16 Hz when a 1 nA/m^2 current was induced by an external field of only 3 V/m.[53]

At the organismal level, a review of 400 studies performed by the Committee on Biospheric Effects of the U.S. National Academy of Sciences did not support the presence of neurophysiological effects during exposure to weak electric fields or extremely low-frequency magnetic fields.[48,54] However, one study revealed that human reactions to sound stimuli are prolonged in an electric field of 10 kV/m (50 Hz).[55] Another group noted a variety of subjective complaints at a 16 kV/m EF.[44] Yet another report that humans could perceive EF of 0.35–1 kV/m was attributed to piloerection.[8] The contradictory nature of these findings underscores the need for additional research.

ELF electromagnetic fields do seem to affect biorhythms, as was clear as early as 1974 for EF of 2 V/m and 10 Hz.[8] Biorhythms of arboreal monkeys were affected after exposure to ELF electric and magnetic fields of 39 kV/m and 0.1 mT (80 A/m).[56] Decreases in nightly peaks of melatonin and acetyltransferase in rats exposed to 1.5 and 40 kV/m electric fields for 3 weeks suggests that their pituitary circadian functions had been disrupted.[8]

Longitudinal observations of humans under constant exposure to EF (380 kV/m) for 20 years revealed no changes in neuroendocrine, biochemical, or hematological variables.[47] This group also was tested under laboratory conditions for the presence of heightened sensitivity to EF at 20 kV/m (50 Hz); none was found. Exposure to a contact electric field, corresponding to an induced EF current of 36 kV/m for 5.5 hours, also did not affect mood, memory, attention, or thinking in these subjects.

Fields up to 100 kV/m have been shown to adversely affect cardiovascular function.[8,54] However, low-frequency magnetic fields (5 Hz to 1 kHz) of flux density 0.1 T (80 kA/m) do not seem to affect human EKG, EEG, blood pressure, or body temperature. Increasing the field intensity to 2.4 T (1.9 MA/m) actually seems to stimulate cardiac activity.[57] Individuals in contact with EF ranging from 3–30 kV/m showed no disruptions in electroencephalographic, cognitive, or cardiovascular function. Similarly, no changes in blood concentrations of thyroxin, cortisol, follicle-stimulating hormone, or testosterone were found as well.[58,59]

2. Hematologic and Immune Responses

Available data on hematologic function, in the opinion of some investigators,[54] are insufficient to reach any conclusions regarding whether exposure to ELF EMR induces stress reactions or other biological changes in human or animal subjects. The few findings of positive or negative shifts in hematologic markers should be checked thoroughly.[8] Most reports of studies involving mice, rats, or guinea pigs have shown no effects of EF up to 50 kV/m on the immunological system.[8] However, possible effects of ELF EF on mitogens and antigens in the human immune response should be investigated.

3. Growth and Development Effects

The effects of low- to extremely-low-frequency EF on fertility, reproduction, and growth are reviewed in Refs. 8, 54, and 60 (see also Fig. 2). In general, the results presented in those works refute the idea that industrial-frequency EF (up to 100 kV/m) adversely affect growth and development. However, exceptions, most of which were reported before 1980, require further clarification. In one study,[61] more birth defects were found in children born to individuals who worked

	Growth	# litters, #neonates per litter	Estrous cycles	#, survival of implanted ova	Behavior & appearance of offspring	# matings, pregnancies	Gonadal morphology	Survival, morphology of embryos	Spermato-genesis
10-100 kV/m	◆OOO					◆			
0.001-0.1 kV/m	◆OO	O	O	O	O		O	O	O

Fig. 2 Effects of 45- to 75 Hz electric fields on reproductive capacity, growth, and development of rodents. Each symbol represents results from one experiment. Solid diamond, effect found; open circle, no effect found. Adapted from Ref. 54.

with high-voltage EF. The same studies revealed increases in chromatid and chromosome aberrations in lymphocytes. However, these findings have not been confirmed by others.[8] British and Swedish reports have suggested possible carcinogenic effects from EF.[63–65] One particularly troubling finding was that children whose fathers had been exposed to EF and MF in their jobs had a higher risk of brain cancers.[65] The incidence of leukemia in children in Austria between 1956 to 1986 reportedly was decreased by a factor of 4, even though the per capita consumption of electricity during that time increased by a factor of 7.5.[62] Although the reliability of these results is open to question, additional investigations are needed to assess any potential associations between ELF EMR and oncological diseases.[8]

A 2 mT MF (1.6 kA/m) has stimulated healing of bone fractures.[11] This intriguing finding suggests that industrial EMR may affect collagen formation in humans, and is of considerable interest for spaceflight applications as well.

Finally, an indirect effect of EF is of particular interest in the spaceflight environment. In weightlessness, many airborne microorganisms are precipitated onto internal surfaces, evidently as a result of electrostatic forces.[66] The electric charge of particles also influences the precipitation of microorganisms and the retention of particulates in the upper respiratory tracts of humans; ionized dust is twice as likely than uncharged dust to be retained.

III. Radiation Safety

Radiation safety encompasses a broad spectrum of issues, ranging from developing, defending, and adopting standards for safe levels of irradiation and radiation-emitting equipment, to implementing protective measures, to maintaining sources of radiation, to training people who work with radiation, and to creating a database on the adverse effects of EMR and related issues. Some of these issues are considered in the following sections.

A. Setting Standards for Radio- and Microwave Frequencies

Setting standards for EMR radiation is a complex process that requires defining criteria and setting levels of risk associated with various situations that range from occupational exposure to accidental overdoses of radiation of different types. The need to approach this monumental task from the point of view of minimizing harm and cost while maximizing benefit requires input from sociologists and ethicists as well as from experts in radiation biology and medicine. The fact that space crews may need yet another set of standards, because of their exposure to unique stresses under conditions very different than those on Earth, further complicates the task of setting standards for spaceflight applications.

Medical, biological, and biophysical considerations for setting standards have been analyzed in Australia, Great Britain, Poland, the former Soviet Union, the U.S., Germany, and Czechoslovakia under the auspices of the WHO and the International Committee on Radiation Protection.[9,67,68] As of this writing, only the energy effects of EMR at radio- and microwave frequencies, i.e., the distribution of absorbed energy as a function of frequency, modulation, and human orientation in the field and contact with the Earth, can be discussed definitively.[69,70]

The specific absorption rate (SAR) has been adopted by Australia, Great Britain, the U.S., and Germany as the basic index of interaction of radiofrequency EMR with biological matter. Occupational exposure limits must account for ergonomic and economic factors as well. For this reason, several EMR dose levels are needed, such as critical (maximum) dose, dose of justified risk (short-term dose), and endurance (continuous) dose. High-stress professions (e.g., nuclear-energy-station operators, pilots, space crews) require special approaches to standard-setting, since small decrements in the ability of such individuals to complete tasks can lead to life-threatening emergencies.

Potentially useful criteria for setting EMR standards include disruption of thermal balance, formation of cataracts, curtailment of life span, and—for animal experiments—death. Other criteria might include chromosomal aberrations, immune dysfunctions, structure of blood-brain barrier components, and cancer incidence.[71] With regard to the radiofrequency range of electromagnetic energy, the risks must be balanced with the benefits derived from it, e.g., radar, television, space communications, and even thermonuclear reactions.

The approach we have used since 1970 to develop standards for EMR in the radiofrequency range[72–74] is based on the radiobiology of ionizing radiation and recommendations from the International Committee of Radiation Safety. Using

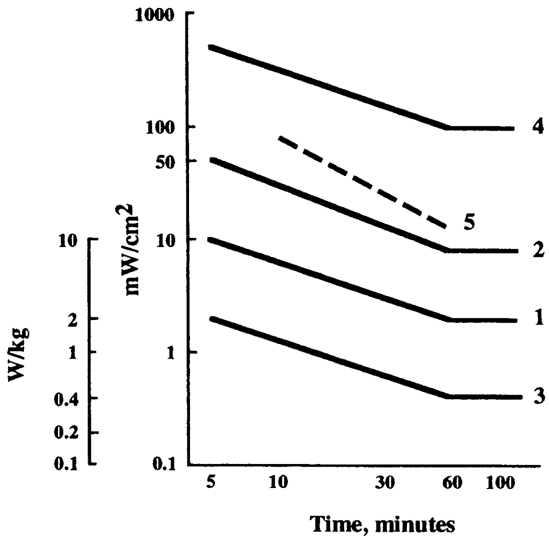

Fig. 3 Threshold values of flux density and specific absorption rate for humans as a function of duration of irradiation (t) under conditions of free space and absence of reflecting surfaces. 1, tolerable flux density for 30–300 MHz (resonance frequencies); 2, tolerable flux density for the remaining frequencies; 3, tolerable specific absorption rate; 4, critical flux density for nonresonance frequencies (obtained by extrapolating experimental data to humans); 5, 1°C increase in body temperature as a function of flux density with frequency of 2.45 Hz (extrapolated data). Adapted from Ref. 80.

results from the literature and from our own research,[24,27,37,75,76] we have developed several unconventional positions from which to set standards for radiofrequency EMR. For example, we found the threshold SAR for microwave irradiation in humans, including a safety factor of 10, to be 0.4 W/kg; absorbed energy was found to be related logarithmically to the duration of irradiation (Fig. 3). The acceptable EMR levels generated with this mathematical function generally coincide with the recommendations of the International Nonionizing Radiation Committee of the International Radiation Protection Association.[6] For example, the IRPA/INIRC limit for radiation energy averaged over the whole body for frequencies over 10 MHz is 0.4 W/kg; for arms, legs, and joints, 20 W/kg; and for other parts of the body, 10 W/kg. However, as noted in the earlier section on defining quantities and units, the concept of absorbed EMR energy for frequencies below 10 MHz is limited, since biological effects essentially reflect the effects of currents induced in the body. Thus, the magnetic field strength is conditional for frequencies below 10 MHz, but generally should not exceed 1.6 A/m.[6]

Standards for radiofrequency EMR have been established for Australia, Bulgaria, Great Britain, Hungary, Holland, Germany, Poland, Russia (U.S.S.R.), the U.S., Finland, France, Czechoslovakia, and Sweden (Tables 2–4). However, these standards are not enforced by law in all countries. Further, occupational-safety standards for space crew members must be based on international law.

Table 2 Soviet safety limits for electromagnetic radiation exposures during an 8-hour work day (Ref. 77)

Frequency, MHz	Electric Field Strength, V/m	Power Density, W/m^2
0.06–3	50	7
3–30	20	1
30–50	10	0.25
50–300	5	0.06
300–3000	10 (continuous)	0.25 (continuous)
	30 (intermittent)	2.5 (intermittent)

At 0.06-300 MHz, exposure limits can be greater, but must must not exceed twice the limits listed here when the duration of exposure to EMF is less than 50% of the work day. For frequencies of 300 MHz–300 GHz, maximum exposure time t equals 2/P (for continuous); 20/P (for intermittent); and P_{max}=10 W/m^2

Table 3 U.S. safety limits for electromagnetic radiation exposure during a 6-minute period (Ref. 68)

Frequency, MHz	Electric Field Strength, V/m	Magnetic Field Strength, A/m	Power Density, W/m^2
0.3–3	632	1.6	1000
3–30	1897/f	4.74/f	9000/f^2
30–300	63.2	0.16	10
300–1,500	3.65f$^{0.5}$	0.009f$^{0.5}$	f/30
1,500–100,000	141	0.35	50

f, frequency

Table 4 IRPA/INIRC recommended limits for electromagnetic radiation exposure (Ref. 6)

Frequency, MHz	Unperturbed RMS field strength E, V/m	H, A/m	Equivalent plane wave power density, P_{eq} W/m^2	mW/cm^2
0.1–1	614	1.6	--	--
>1–10	614/f	1.6/f	--	--
>10–400	61	0.16	10	1
>400–2,000	3/f$^{0.5}$	0.008f$^{0.5}$	f/40	f/400
>2,000–300,000	137	0.36	50	5

IRPA/INIRC, International Nonionizing Radiation Committee of the International Radiation Protection Association; RMS, root-mean-square

The induced current from contact with metal objects must be limited to minimize the risk of burns. In the worst case, this can be achieved by decreasing E from 614 V/m to 194 V/m at f =0.1–1 MHz, and from 614/f to 194/f$^{0.5}$ for f > 1–10 MHz.

The standards drafted for the former Soviet Union[77,78] have been corrected for local irradiation of the hands at frequencies of 0.3–300 GHz. Although Gandhi[79] has criticized U.S. ANSI standard C95.1.1982 as being too high, we contend that the power-density limits can be increased safely if exposure time to some frequencies is reduced.[80] We found that risk from the entire radiofrequency spectrum of EMR can be estimated by using a method of competing frequencies or bands.[81] Because the accuracy of EMR measurements at this time is only about 50% (about 2–3 dB), a 1 mW/cm^2 standard should be considered to denote a 0.5–2.0 mW/cm^2 range.[71]

Evaluating effective doses of EMR in the radio- and microwave frequency range is problematic, especially for pulsed, fractionated, or prolonged irradiation. EMR quality coefficients (e.g., frequency, grounding, reflecting surfaces) should be considered, as should the temperature of the environment and the presence of ionizing radiation or weightlessness. Space crews may work with on-board radiation sources at 40–70 MHz frequencies, at which estimates of local SAR and effective dose are vague. Other problems in estimating biological effects are associated with EMR modulation. Nonetheless, occupational standards should pertain to the appropriate effective dose, establishment of which requires further work in this area.

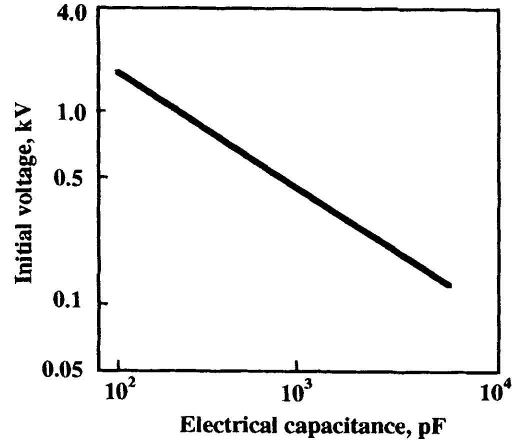

Fig. 4 Threshold voltages for humans to sense capacitance discharges at 60 Hz. Adapted from Ref. 8.

B. Extremely Low-, Superlow-, and Ultralow-Frequency Electric and Magnetic Fields

Setting safety standards for individuals exposed to EMR frequencies between 3 Hz and 3 kHz requires a different approach from EMR of other frequencies. As stated earlier, for frequencies greater than 10 MHz, the main indicator of dosimetry is specific absorption rate; at frequencies below 10 MHz, the main variable is the density of the current induced in the body.

Both electric and magnetic fields can induce electrical fields and currents inside the human body. For example, a magnetic field of 65 mT (at 60 Hz) induces a current of 1 A/m^2; a 65 μT field at the same frequency induces a 1 mA/m^2 current. Currents induced in the human body can be computed from the magnitude of external unperturbed fields, the frequency, shape, dimensions, and spatial orientation of the body.[2]

In general, the biological effects of induced current density from whole-body exposure to 50/60 Hz fields are as follows: 1–10 mA/m^2 (induced by magnetic flux densities between 0.5 and 5 mT) produces only minor biological effects; 10–100 mA/m^2 (5–50 mT) produces well-established effects on the visual and nervous systems; 100–1000 mA/m^2 (50–500 mT) stimulates excitable tissue, and produces potential health risks; and more than 1000 mA/m^2 (more than 500 mT) can produce extrasystoles and ventricular fibrillation, i.e., acute health hazards.[13]

The IRPA/INIRC recommends that the exposure limit for EF and MF (50–60 Hz) be restricted to that which induces no greater than a 10 mA/m^2 current in the human body.[2] The maximum amount of EF and MF to which individuals should be exposed during an 8-hour day must not exceed 10 kV/m, with induced current density no greater than 4 mA/m^2 (0.5 mT). Brief exposure to EF between 10 and 30 kV/m is acceptable if $Et \leq 80$ for the work day, where E is the electric field, in kV/m, and t is time, in hours. For MF, the maximum for a work day is 0.5 mT; short-term exposures to 5 mT MF must not exceed 2 hours per day. (Typical average MF exposures in offices and houses range from 0.01 to 1 μT, although they can reach 1 mT near some appliances.) Short-term exposures restricted to the limbs should not exceed 25 mT.

Soviet standards for exposure to electric and magnetic fields are as follows. Short-term occupational exposure to external electrostatic fields between 20 and 60 kV/m should be limited to $60/t^{1/2}$, where t is the exposure duration in hours.[82] The limit for exposure to constant MF is 10 mT (8 kA/m).[83] Continuous occupational exposure to EF (50 Hz) over an 8-hour day should be limited to 5 kV/m.[84] Short-term occupational exposure to electric fields ranging from 5–20 kV/m is acceptable for $t=50/(E-2)$, where E is the electric field in kV/m and t is time in hours; thus, the maximum time to which an individual can be exposed safely to a 25 kV/m EF is 10 minutes. Limits for ELF MF are 4 mT (3.2 kA/m) for whole-body exposure and 6.5 mT (5.32 kA/m) for localized exposure.

Transient capacitance discharges and steady-state contact currents also are of interest from a safety standpoint. Transient capacitive discharges can occur between a person and a charged object by means of a spark through an air gap. Human reactions to the transient electric shocks from spark discharges depend on the discharge voltage and the capacitance of the discharging object (Fig. 4). Women are more sensitive to capacitance discharges, which may be associated with the linear relationship between sensitivity to transient discharges and body mass.[85]

Steady-state 50 or 60 Hz current from contact with charged objects can produce biological effects that range from barely perceived to ventricular fibrillation and death.[74] The "let-go" thresholds, i.e., the maximum current an individual can tolerate and still release a conductor by using the muscles directly

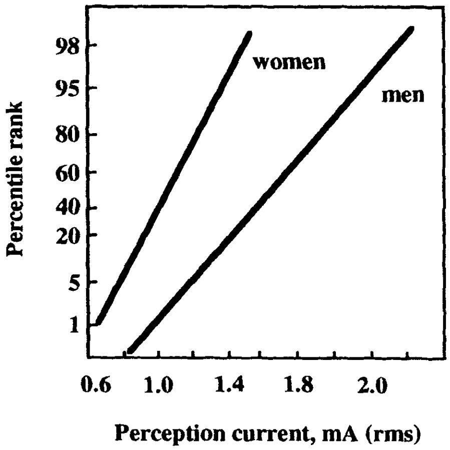

Fig. 5 "Let-go" currents for adult men (n=134) and women (n=28). The maximum uninterrupted reasonably safe currents, taken from the 0.5 percentile values, are 9 mA for men and 6 mA for women. Reproduced with permission from Ref. 86.

stimulated by that current, for men and for women are illustrated in Fig. 5.[86] The severity of an electric shock from touching a charged object depends on several factors, including grounding conditions, the magnitude of contact current, the duration of current flow, and body mass. For example, the 15 kV/m field near high-voltage power lines can induce currents in an insulated human of up to 225 μA; in a large insulated object such as a car, this current can reach 7.5 mA. A grounded person who contacts such an object will receive a substantial electric shock. This situation must be considered in protecting cosmonauts in the event of emergency landings on or near high-voltage power lines or charged, ungrounded objects.

In our opinion, studies of the processes underlying the human response to ELF EMR should emphasize the CNS, reproductive functions, and the combined effects of EMR with environmental toxins. Additional emphasis should be placed on obtaining reliable data regarding possible carcinogenic effects of this type of radiation.

C. Video Display Terminals

Potential health risks from using video terminals have been the focus of concern during the past 10 years, chiefly in association with several news reports on this topic. These often contradictory reports described effects such as asthenopia, cataracts, skin diseases, teratogenic effects and miscarriages, and even photogenic epilepsy.

In 1985, the WHO published an extensive review of experimental and epidemiological studies on the health effects of using visual display terminals.[87] The conclusions drawn by the WHO working group pertain primarily to video terminals with cathode-ray tubes with plasma, electroluminescent, or liquid crystal screens, but can be extended to include cathode-ray oscillographs, radar, and measurement devices with display screens. Details of measurements of EMR, EF, and MF around video display units are presented in Table 5 and are summarized below.

According to the U.S. Bureau of Radiological Health, terminals operated under the greatest stress and the worst conditions (poor components, breaks in lines) produced ionizing radiation that was greater than baseline levels in only 14 cases, and ranged from 4.4 to 17.6 μGy per hour.[87] Under optimal operating conditions, radiation exceeded baseline only once, and amounted to only 2 nGy per hour. Another study of 57 industrial uses of video display terminals revealed very low X-irradiation (3×10^{-9} Gy/hour).[88] Thus, the maximum annual dose to individuals working 2000 hours per year would be 6 μGy/year (0.018 μSv/year). For comparison, the annual dose received by humans from ^{40}K is 3 μSv/year.

Video display terminals are not a source of microwave irradiation.[89] Between 1 and 200 MHz frequencies, electric field intensities range from 1 mV/m to 0.5 V/m at a distance of 1 m from the screen, and magnetic field intensities from 0.1 to 200 μA/m 5–30 cm from the screen. The highest intensity was recorded at frequencies of 3–30 MHz. For frequencies between 3 kHz and 3 MHz, the EF strength reached 150 V/m and the MF strength 0.2 A/m. EF and MF levels of 165 V/m and 0.7 μT have been measured at some terminals.[90] Figure 6 illustrates the distribution of ELF EF from a video display terminal, measured with a meter having a frequency range of 10 kHz–200 MHz.[91] In the 10–200 kHz range, the greatest specific absorption rate is 50 mW/kg.[92] For comparison, the MF level (5–500 Hz) from fluorescent lamps ranges from 0.064–0.188 A/m; from a color TV (2 m from the screen), 0.036 A/m; from an electric typewriter, 1.64 A/m; from a pocket calculator, 0.558 A/m; from a hand mixer, 9.295 A/m; and from an electric teapot, 0.7223 A/m.[93]

The electrostatic field around a computer terminal ranges from 8 to 75 kV/m.[94] According to one study that included 78 measurements, users were exposed to a mean electrostatic potential of +0.6 kV/m.[95] The user's own electric potential influences the deposition of particles on the body surface, which in turn can lead to rashes and other skin ailments; however, at least one group has found no epidemiologic evidence of an association between skin eruptions and duration of work.[95] Reports of increased rates of miscarriage among women working with video displays,[96] and demonstration of teratogenic effects in chicks exposed to MF of 0.12–12 μT intensities, have given rise to much concern. However, a careful statistical analysis[97] of seven areas in the U.S. and Canada in which miscarriage rates were high revealed this phenomenon to be random, and not associated with video terminal use. This conclusion also was supported by WHO experts.[87]

In summary, both the IRPA/INIRC[98] and WHO[87] have concluded that no health risks are associated with EMR from video display terminals. Thus, we see no scientific rationale for developing protective devices or radiation monitoring for these devices. However, since the number of people who work with video display units is increasing rapidly, other occupational aspects of working with these devices, e.g., ergonomics, should be studied further.

Table 5 Forms of electromagnetic radiation from video display terminals (Ref. 87)

Spectrum	Band	Upper limit emitted	Applicable standard
X-rays[a]	> 1.2 kV	< 0.1 mSv/yr	5–10 mSv/yr
UV-B, UV-C[a] (actinic)	200–315	0.3 J/m^2 (8 hrs)	30 J/m^2(24 hr)
UV-A[a]	315–400 nm	0.1 W/m^2	10 W/m^2
Visible light[a]	400–700 nm	2.5 W/m^2	10,000 cd/m^2
Near-infrared[a]	700–1500 nm	0.05 W/m^2	100 W/m^2
Far infrared[a]	1050 nm–1 mm	4 W/m^2	100 W/m^2
Microwaves[b]	0.3–300 GHz	not detected	10–100 W/m^2
High to ultrahigh frequency[b]	3–300 MHz	0.5 V/m 0.0002 A/m	600 V/m 0.2 A/m
Medium to very low frequency	3 kHz–3MHz	150 V/m	100 V/m
Very low frequency[b]		0.1 A/m	1.6 A/m
Ultralow frequency	0-3 kHz	65 V/m[c] 0.2 A/m	2–10 kV/m
Electrostatic field[b]	0 Hz	15 kV/m[c]	20–60 kV/m

[a]measured close to screen
[b]measured 30 cm from screen
[c]does not apply to unperturbed fields

Most measurements were averaged over time and over screen area; every fundamental EMF frequency contains several harmonics with higher frequencies.

D. Administrative Aspects of Radiation Safety

Some of the most complex aspects of protecting humans from EMR are administrative. With regard to occupational conditions, some administrative principles of radiation safety include scheduling the work day and configuring the workplace so as to minimize contact time with sources of EMR; excluding coupling effects, e.g., from reflecting surfaces and grounding of operators; and establishing safety procedures to be used in emergencies.

Frequently, emergency situations may involve more than one factor, such as ionizing radiation, electrical hazards, and others. In our opinion, EMR is the least dangerous of these factors. Nonetheless, individuals who work with EMR, including space crews, must be given clear instructions as to the boundaries of harmful effects from it, including relations of risk from EMR with that from other factors such as ionizing radiation, weightlessness, chemical pollution, high temperatures, and noise. Sparks and electric discharges are more likely at certain intensities and frequencies, particularly those less than 10 MHz. Because flame-retardant clothing can become electrified, medical standards for equipment must be below "safe" EMR levels. Also, some metal items (e.g., frames for eyeglasses) can focus or increase the local field levels of microwave EMR.[99]

The cost of generating and defending occupational safety standards can be minimized through efforts to account for future increases in the power of electromagnetic sources and in technological progress. The ergonomics of EMR factors associated with new techniques also are an important aspect of safety assessments. One scheme for evaluations of this type is outlined in Fig. 7.

With respect to spaceflight, international standards should be used regardless of which country sponsors or launches missions. The applicable standards for EMR are those recommended by the IRPA/INIRC. However, because technical difficulties occasionally preclude maintaining these standards at all times during spaceflight, the importance of procedural or administrative measures in protecting astronauts and cosmonauts must not be underestimated.

IV. Earth and Near-Earth Electromagnetic Fields

Heliophysical factors that can affect living things can be classified in three groups: galactic and planetary processes; processes occurring on the sun; and geophysical factors associated with processes occurring in the atmosphere, hydrosphere, and lithosphere. Detailed information on the physical characteristics of interplanetary space is provided in Refs. 1 and 100, as well as in Volume I of this series (Chapter 2, Pisarenko et al.).

In brief, the spectrum of solar EMR extends from the radiofrequency band to the X-ray region. The electric com-

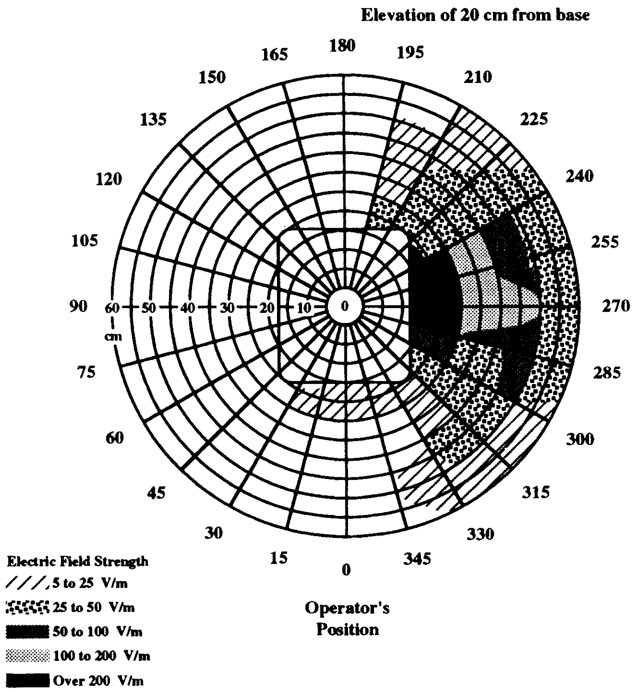

Fig. 6 Distribution of very-low-frequency electrical fields (measured from 10 kHz–200 MHz) around a video display terminal. This view is from the top of a horizontal cross-section taken at 20 cm above the base of the unit, roughly at the middle of the screen. Reproduced with permission from Ref. 91.

ponent of the EMR of the Earth created by solar activity fluctuates from 10^{-2} to 10^{8} mV/m/Hz. The mean intensity of the EF at the surface of the Earth is 120–150 V/m. During electrical storms, however, the EF can reach 10 kV/m (at 10 kHz); even at 10 km from the discharge, the EF can exceed 3 kV/m. The biological and physicotechnical aspects of EMR from lightening discharges undoubtedly are of interest in evaluating technologies that create ultrashort, low-frequency EM impulses.

The Earth's MF is about 0.05 mT, and varies diurnally by about 50 nT, and by up to 1000 nT during magnetic storms. Variations in the magnetic field are related also to solar activity, which changes over 11-year and 27-day periods. The Earth's magnetic field is significantly greater than that of the moon (by 10^{-6} times), Venus (10^{-4}), and Mars (2×10^{-4}). Jupiter, by contrast, probably has the strongest radiation belts and magnetosphere in the solar system[1]; it is surrounded by powerful sources of radiation in the decimeter and decameter band ranges, and its magnetic moment is 10,000 times that of the Earth.

Temporal variations in the intensity of the field aboard a spacecraft moving through near-Earth space are significantly greater than the variations in the Earth's natural magnetic field.[101] The MF created aboard a stationary spacecraft by the Earth's external magnetic fields have three major periods of oscillation: a period equal to the period of rotation of the spacecraft; half the period of revolution; and half the period of oscillation. When the spacecraft moves, the pattern of MF on board is more complex; at an altitude of 280 km, over a quarter-period of revolution, the magnetic field strength changes at a mean rate of 1.5–22 nT/s.

Much of the background from which we review the effects of geomagnetic and weak MF comes from works published in the USSR,[102–106] although a few studies of "weak" interactions of EMR with biological systems have been reported by Western scientists as well.[49] In general, studies have focused on the effects of geo- or hypogeomagnetic fields on neural and cardiac function; hormones, biologically active substances, and enzymes; biorhythms; and remote intercellular reactions. Attention also has been devoted to exploring the putative link between geomagnetic disturbances and the risk of accidents, and the mechanisms that could underlie the effects of weak low-frequency EMR characteristic of near-Earth space.

Analyzing the effects of environmental factors such as the Earth's MF on physiological measures is difficult because of the complexity and interrelationships among these factors and measures. Moreover, both the absolute value of an environmental factor and its rate and extent of change undoubtedly influence the physiological outcome. For this reason, analytical methods for heliophysical factors are unusual, and have included superimposed epochs, direct comparisons, least-squares correlations and regression analyses, and Chebyshev's method of solving correlation equations. A FORTRAN program also has been proposed to compare geophysical and physiological factors.

A. Geomagnetic Fields and Their Effects on Humans

Although the Earth's magnetic field has been suspected of influencing virtually every vital physiological function,[106,107] experimental results have tended to be ambiguous, and occasionally contradictory. The frequency of the Earth's EMR is close to that of several biological rhythms (Fig. 8), particularly between 7 and 10 Hz. Magnetic storms are thought by some[107] to influence physiological indicators such as respiration rate, blood pressure, and body temperature; the Z (vertical) and D (horizontal) components of magnetic disturbances are thought to have less of an influence, and the H (radial and tangential) components of the K-index (which compares the intensity of geomagnetic disturbance over time) still less.[107] Deryapa's analysis of associations between 23 physiological measurements and the K-index[102] revealed correlations only for neutral 17-ketosteroids, riboflavin concentrations in the blood, skin temperatures, and rate of blood flow. In another study, changes in production of histamine, acetylcholine-like substances, and cholinesterase were noted in a group of people with ischemic heart disease, as well as shifts in 17-ketosteroid excretion.[108] The investigators of this latter study also found that the relative proportions of cytochrome-oxidase isoenzymes, and blood ATP concentrations, change during geomagnetic disturbances in individuals who have rheumatism.[108]

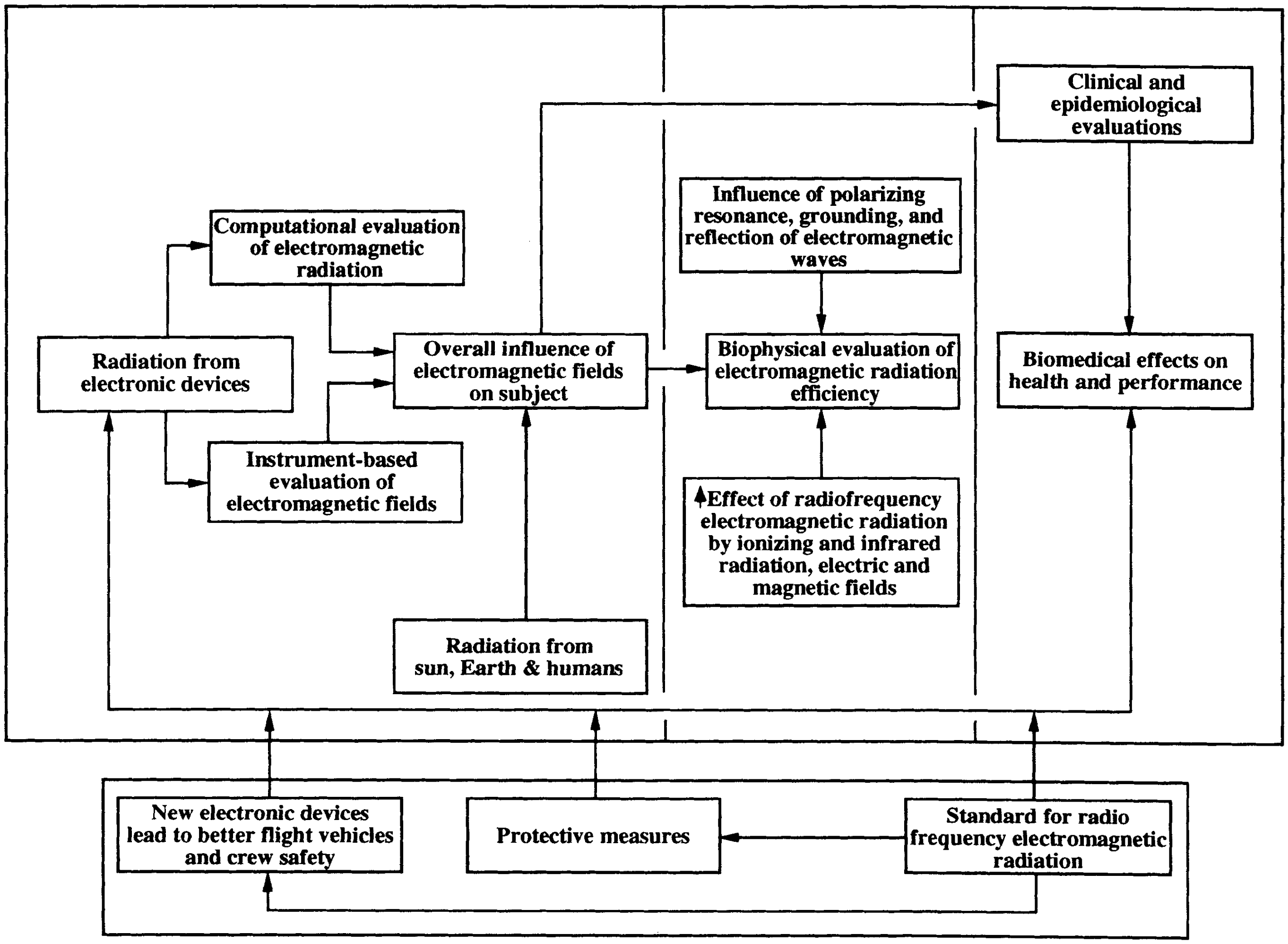

Fig. 7 Flow chart for ergonomic evaluations of new technology for electromagnetic-radiation factors. Adapted from Ref. 72.

Magnetic disturbances during the day affect human sleep patterns, increasing the frequency and periodicity of sleep stages in such a way as to lessen the amount of deep sleep during such periods.[107] During a period of low solar activity in 1975, the degree of psychosis in psychiatric patients was found to fluctuate with MF, increasing as nanoteslas became tens of nanoteslas in oscillation periods of 5 to 150 s.[108] The number of flight accidents reportedly increased during periods of solar activity as well.[109] However, an extensive review comparing the annual incidence of disease with that of accidents between 1946 and 1976 revealed no correlations with indicators of solar and planetary geomagnetic disturbance (Fig. 9), a conclusion reached by American investigators as well.[110]

Mansurov and others[107] associated changes in interplanetary MF with increased neuropsychological disturbances in "maladjusted" individuals. The authors associated irritation during the first days after sector sign changes with the disappearance of a certain type of short-wave radiation, and noted an increase in cardiac arrhythmias, autonomic-vascular paroxysms, and symptoms of stenocardia (angina pectoris). Later assessments[107] did not confirm these correlations, but revealed insignificant decreases in the number of errors (time to perform tests of working memory) and slight psychological activation.

Rayevskaya[106] found associations between geomagnetic disturbances and psychological and cardiovascular dysfunction in both healthy and ill individuals. Aspects of attention, short-term, and long-term memory deteriorated and simple motor-reaction time increased in both groups. Interhemispheric asymmetry was said to diminish, and the time needed to process visual information shortened.[106] However, in healthy individuals these changes did not exceed physiological norms, and thus their significance is limited to people who are ill.

In conclusion, few of the correlations reported for heliobiological factors have withstood rigorous statistical analysis. Nevertheless, given the complexity of the analyses needed, and the contradictory nature of many of the results, further study is warranted. At least one report[103] has emphasized the need to consider factors other than geomagnetic fields, e.g., atmospheric infrasound and oscillations in concentrations of atmospheric radon. Interestingly, retrospective comparisons of current and past heliobiological data re-

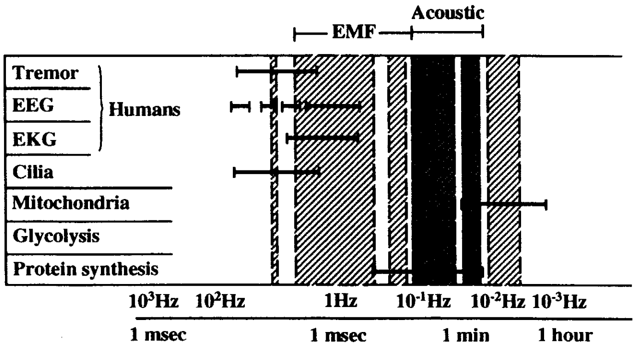

Fig. 8 Biorhythm frequencies in humans and in other organisms as a function of electromagnetic-frequency and acoustic-frequency (darker shading) oscillations in the environment. Reproduced from Ref. 103.

veal that heliobiological associations tend to disappear over time.[110] Thus, the question of how periodic and episodic natural EMR, in combination with other environmental and social factors, will affect healthy or ill humans remains unclear.

B. Hypogeomagnetic Fields: Phenomenon or Artifact?

The electric and magnetic quasistatic fields of Earth, atmospheric electricity and lightning discharges, and solar and galactic radiation all represent stressors to which humans have adapted throughout evolution. For this reason, a decrease in the intensity of such factors in space might be expected to have some effect on space crews during flights. At a distance of 8 to 40 Earth-radii from Earth, the induced MF aboard a spacecraft during a period free of solar flares fluctuate between 1 and 30 nT; during periods of magnetic disturbance, they increase by a total of 12–15 nT.

Much attention was focused on biomagnetic fields in the former Soviet Union between 1970 and 1980, as reflected in the large number of reports published during that time.[111] Experiments on the effects of weak MF on animals (Table 6), humans, tissue cultures, and plants have generated mostly inconclusive or contradictory results. Some early experiments suggested that weak MF were carcinogenic; however, subsequent experiments did not confirm this observation. Beisher[111] noted a decrease in critical flicker-fusion frequency in astronauts exposed to 50 ±30 nT MF before a lunar flight, but body mass, temperature, respiration rate, EEG, EKG, and psychological measures were unchanged. Although many changes were noted in the organs of rabbits developing in utero under hypogeomagnetic conditions, those changes were believed to be reversible.[111]

Individuals confined in a concrete bunker, which decreased the Earth's MF by a factor of 100, showed increased periods of circadian rhythms and changes in reaction time.[111] However, the effects of other factors such as isolation, atmospheric composition, psychological compatibility, and others in this facility cannot be ruled out. Nonetheless, studies such as these are useful for understanding how hypogeomagnetic fields might

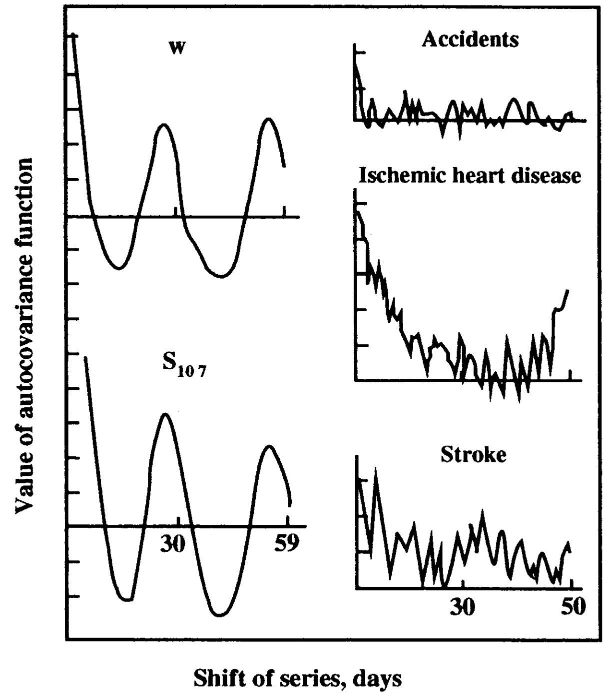

Fig. 9 Autocovariance functions for several values of W, S indexes (attesting to the existence of periodic components) and death rate (attesting to the absence of periodic components) from accidents, ischemic heart disease, or stroke. Adapted from Ref. 110.

affect space crews, particularly those crews that travel to other planets.

In our opinion, these observations are too few to support the existence of biological effects from hypogeomagnetic fields. Obtaining absolutely reliable data would require a strict experimental approach that accounts for many more factors than have been studied in the few experiments conducted to date.[104]

V. Biomedical Consequences of Ultraviolet Radiation

The most biologically active component of the sun's UVR, that with wavelengths less than 180 nm, is absorbed almost completely by the Earth's atmosphere. Although most of the long-wave component (320–400 nm) of UVR reaches the surface of the Earth, its biological effectiveness is slight. However, radiation at intermediate wavelengths of 180–320 nm, although partially absorbed by the ozone layer of the stratosphere, significantly influences both the biosphere and humans.

Biomedical effects of UVR are evaluated on the basis of biologically effective intensity, which is measured by multiplying the incident spectral intensity by the action spectrum, followed by summation across the entire spectrum of radiation.[112] The effectiveness of radiation at the maximum of the action spectrum is set at one, and the magnitudes of biologically effective intensities and cumulative doses are expressed as percentages of this maximum. The most sensitive, and best

Table 6 Hypomagnetic-field effects on animals

Species	Field strength, nT (exposure duration)	Tests	Results
Mice	100 (4–12 months)	Development, reproduction, teratogenic effects, behavior, morphological changes in organs, blood, increase in tumors.	+
Mice	50 (4–12 months)	Development, reproduction, teratogenic effects, behavior, morphological changes, blood, increase in tumors.	–
Mice	100 (up to 3 months)	Development, blood (enzyme components, electrolytes), behavior, mitotic activity of the corneal epithelium, diurnal rhythms.	–
Rats	50–100 (3–8 days)	Morphological and histochemical analyses in the liver, spleen, adrenal cortex (level of glycogen, SDH).	+
Rabbits	80 (18 hours)	Phagocyte activity of leukocytes, activity of alkaline and acid phosphatases, transaminase in microphages.	+
Rabbits	50–150	Postnatal death rate and variance in weight of baby rabbits born to mothers exposed to hypomagnetic fields during pregnancy. Fat deposits in kidneys, heart (symptoms of myocardial dystrophy) and abdominal cavity. Morphological and histochemical changes in the lungs, spleen, and stomach in the baby rabbits during the postnatal period.	+
Rats	290	Behavior, learning, physical endurance, cardiovascular status.	+

studied, organ systems with respect to the effects of UVR are the skin, the eyes, and the immune system.

A. Dermal Effects

Irradiation of the skin in relatively high doses induces aseptic inflammation or erythema ("sunburn"). These effects reflect death of epidermal cells, with subsequent denaturation of proteins and enzymatic transformation of the resulting products into biologically active substances, the most important of which is histamine. The spectrum of the erythemic action of UVR reaches maximum at 297 nm and drops sharply at about 280 nm, followed by an increase in effectiveness as the wavelength decreases further.[113] The minimal erythemic dose varies as a function of ethnic and racial differences in skin pigmentation; its mean value for normal untanned skin is taken to equal 200 J/m^2 (Ref. 114). At such doses, erythema develops one to eight hours after exposure, and persists for a day or more; as the dose increases, the latency period becomes shorter and the severity and duration of erythema increase. An important consequence of high-dose irradiation is suppression of perspiration, decrease in the sensory sensitivity of the skin, and worsening of overall physiological status. The latter evidently is due to the release of excessive amounts of physiologically active substances into general circulation.[115,116] Erythema also activates the synthesis of DNA, proteins, and the protective pigment melanin.[117] The action spectrum for stimulating melanin synthesis resembles the erythema-sensitivity curve; however, a long-wave (300–400 nm with maximum of 340 nm) action spectrum also exists for increased pigmentation that develops without erythema.

When low-intensity irradiation is chronic, skin changes can occur even in the absence of erythema.[118] The overall tonic effects of UV irradiation primarily are a result of physiologically active substances entering the bloodstream. The continued activation of melanin, DNA, and protein synthesis increase pigmentation and thicken the corneal skin layer, thus increasing its resistance to subsequent irradiation. Nonetheless, multiple, long-term exposures to UVR from the sun have long-term consequences. The skin loses its surface architecture, the fibers of its deep layers are damaged, and it becomes fragile and subject to damage from minimal trauma. Degenerative changes in elastic tissue (solar elastosis), considered precancerous by some,[119] is an irreversible condition and is accompanied by a change in the functional state of the skin. Specific reactions of skin to short-wave (less than 280 nm) radiation includes earlier development and faster diminishment of erythema, weak, transient pigmentation, and pronounced symptoms of solar elastosis and skin aging.[120]

B. Cholecalciferol Synthesis

UVR plays an important role in supplying the body with cholecalciferol (vitamin D_3), which regulates phosphorus and calcium metabolism. In the presence of UVR, 7-dehydrocholesterol from the oil glands of the skin is converted to vitamin D_3, which is absorbed by the skin. Vitamin D_3 deficiency induces rickets and dental caries. The action spectrum for the synthesis of this vitamin is analogous to that for erythema and peaks at 295 to 300 nm. The UVR dose needed to compensate for a deficiency in vitamin D_3 is 60 mean erythemic dose (MED) units on the uncovered portions of the body.[121]

C. Immunosuppression, Mutagenesis, and Carcinogenesis

Immunosuppression from UVR exposure takes place in tanned and untanned individuals and is not correlated with erythema. The surface layers of the skin contain urocanic acid, a photoreceptor for immunosuppression. UVR isomerizes this compound, which in turn is followed by a change in antigen-presenting cell function and an increase in the number or activity of lymphocyte suppressors.[122] As a consequence, the body's resistance to tumor cells is suppressed, as are contact- and delayed-type hypersensitivity to various antigens. Humoral immunity either is unchanged by UVR, or may be activated after several small doses.

Immunosuppression is apparent after exposure to 250 to 320 nm (peaking at 270 nm); it does not depend on radiation intensity, and is determined only by total dose.[122] Brief exposure to low doses of UVR induces only local effects in the irradiated areas, but the entire immune system suffers when exposed to high cumulative doses.[123] Local hypersensitivity is suppressed at doses of 200–800 J/m^2, but systemic depression does not appear until doses reach twice that amount. The dose that suppresses tumor immunity approximates the carcinogenic dose ($1–2 \leftrightarrow 10^5$ J/m^2). Thus, photoimmune reactions probably are one reason for the increased frequency of skin cancers in people who live in areas with intense natural UVR.[124] UVR-induced immunosuppression also may decrease resistance to infectious diseases,[125] or the efficacy of vaccines.

Mutagenesis and immunosuppression are thought to play major roles in UVR-induced carcinogenesis.[124] UVR can induce squamous-cell and basal-cell carcinomas and melanoma.[126] Carcinomas are the more common; they tend to remain local, and can be excised fairly easily. Melanomas, in contrast, account for only 5–8% of skin tumors, but they grow quickly, metastasize early, and can be lethal. The oncogenic action spectrum of UVR is close to those for erythema, suntan, and vitamin D_3 synthesis,[127] and thus the risk factors for skin cancer (light skin, blue eyes, freckles and moles, red hair) are correlated with low-MED skin type.[126] The carcinogenic effect of UVR accumulates over long periods; rare periods of intense radiation are much more dangerous than frequent exposure to lower doses. Although some investigators maintain that no threshold for mutagenesis exists, the effective dose of UVR for carcinogenesis is relatively high (see above), and thus skin cancer develops over many years, even in areas that have a high intensity of natural UVR.

D. Ocular Effects

UVR frequently produces acute inflammation of the cornea and conjunctiva. Depending on the intensity and dose, this condition develops 0.5–24 hours after irradiation, and is accompanied by the sensation of something being in the eye, tearing, photophobia, and blepharospasm. These symptoms typically peak on days 1–3 and diminish after 2–7 days. Unlike the skin, the eyes do not become tolerant to UVR, and thus the same symptoms appear after subsequent exposures. The action spectrum for induction of "photokeratoconjunctivitis" peaks at 270 nm. The minimal effective dose is equal to 40 J/m^2 at high intensities, and increases as intensity diminishes.[128]

This syndrome can significantly affect visual function. The ability to track moving objects declines, as does the passage of visible light through the cornea; the ability to focus images on the retina probably is impeded as well.[129,130] The reactivity of the retina itself also decreases.[131] This last effect develops after the keratoconjunctivitis symptoms disappear; it persists longer and affects light sensitivity to a much greater extent than do changes in the cornea.

Prolonged exposure to UVR can result in cataracts, corneal and retinal degeneration, pterygium, and melanoma in the eye vessels.[132] By far the most common of these syndromes is cataract,[133] which can greatly impair resolution, contrast, and figure recognition. The action spectrum for cataractogenesis peaks at 300 nm; the minimal effective dose is about 10^3–10^4 J/m^2 (Ref. 134).

E. Ultraviolet Radiation Standards for Spacecraft

Sources of UVR aboard spacecraft are solar rays penetrating the windows, bactericidal lamps, and any special radiation treatments that might be used to improve nonspecific physiological resistance or to compensate for vitamin D_3 deficiencies. The chief concern in ensuring the safe use of UVR involves selecting radiation of spectral energy that maximizes the putative therapeutic effect while minimizing dangerous side effects. For example, the maximum radiation spectrum of bactericidal lamps must be lethal to microorganisms, 260 nm.[135] Of the existing commercial sources of UVR, low-pressure mercury lamps radiate more than half their energy at a wavelength of 254 nm.[121] However, radiation of this type detrimentally affects health, since its spectral peak corresponds to that for immunosuppression, photokeratoconjunctivitis, and solar elastosis. Moreover, the spectrum of low-pressure mercury lamps is outside the zone of the maximum spectra for stimulating vitamin D_3 synthesis and the tonic effect of UVR.

The peaks of the action spectra for both positive (synthesis of vitamin D_3, tonic effect, suntan) and negative (carcinogenesis, cataractogenesis) effects of UVR are near 300 nm; however, the negative effects involve higher effective doses and longer latency periods. Thus, negative effects can be minimized by limiting radiation intensity and dose as well as selecting appropriate wavelengths. Of the therapeutic UVR

Table 7 Maximum permissible dose and action spectrum of 200–315 nm ultraviolet radiation during an 8-hour work day

Wavelength, nm	Maximum dose, J/m^2	Relative spectral effectiveness
200	1,000	0.03
210	400	0.075
220	250	0.12
230	160	0.19
240	100	0.30
250	70	0.43
254	60	0.50
260	46	0.65
270	30	1.00
280	34	0.88
290	47	0.64
300	100	0.30
305	500	0.06
310	2,000	0.015
315	10,000	0.003

Table 8 Maximum permissible daily dose of ultraviolet radiaiton of 200–350 nm for exposure periods up to 10 years (Ref. 138)

Wavelength, nm	Daily dose, J/m^2	Wavelength, nm	Daily dose, J/m^2
200–302	3.0×10^1	313	4.0×10^3
303	4.0×10^1	314	6.3×10^3
304	6.0×10^1	315	1.0×10^4
305	1.0×10^2	320	1.6×10^4
306	1.6×10^2	325	2.4×10^4
307	2.5×10^2	330	3.7×10^4
308	4.0×10^2	335	5.6×10^4
309	6.3×10^2	340	8.6×10^4
310	1.0×10^3	345	1.3×10^5
311	1.6×10^3	350	2.0×10^5
312	2.5×10^3		

lamps available in the former Soviet Union, the Westinghouse LE-30, LER-40, and FS-40 have maximal radiation spectra at around 310 nm.[121] The slight short-wave component of the radiation spectrum from these sources can be filtered out.

As noted earlier, UVR wavelengths less than 300 nm are absorbed by the Earth's atmosphere; thus, the biologically effective intensity of space radiation can be 1.5 to 2.5 times greater than radiation at the Earth's surface.[136] Various portions of the solar spectrum can be used for bactericidal and therapeutic purposes. The advantages of this approach arise from the potential for simulating the spectral-energy aspects of UVR at the Earth's surface, to which humans already are significantly adapted. Promising artificial sources of UVR also can be developed for this purpose.

Because most of the information on biological effects of UVR has been obtained through epidemiological studies and simulations with laboratory animals, deriving maximum acceptable levels of UVR for the range of associated medical effects has been difficult. However, some maxima have been set. In the U.S., standards have been developed by the National Institute for Occupational Safety and Health and adopted by the American Conference of Government Industrial Hygienists.[112,137] These standards are based on the action spectra for photokeratoconjunctivitis and erythema for healthy white individuals, and are applicable only for acute UV radiation effects. Some of these U.S. standards are given below.

For wavelengths ranging from 315–400 nm, the irradiation intensity for unprotected skin and eyes must not exceed 10 W/m^2 when exposures last 1000 seconds or less, and the integral dose during such periods must not exceed 10,000 J/m^2. For wavelengths of 200–315 nm, the maximum acceptable level of irradiation for unprotected eyes and skin is determined as follows. If monochromatic radiation is used, the integral dose over an 8-hour work day must not exceed the values presented in Table 7. When polychromatic sources are used, the standard for the biologically effective dose is set relative to 270 nm. UVR intensity must not exceed 30 J/m^2 over an 8-hour work day. These standards are not applicable to people with heightened photosensitivity.

The standards adopted by the Ministry of Health of the Netherlands are stricter[138]; the maximum acceptable daily doses for total exposure durations ranging from 1 day to 10 years are presented in Table 8. The standards for the U.S. and the Netherlands are the same only at 315 nm. A daily dose of 30 J/m^2 is acceptable in the U.S. standards only for 270 nm, but for 200–302 nm in the Netherlands standards. Acceptable doses in the Netherlands scale for 305 and 310 nm are five times and two times less, respectively, than those accepted in the U.S.

Undoubtedly, the standards for the Netherlands attribute greater biological effectiveness to UV radiation in the 300 nm region than those of the U.S., presumably because of the probability of developing photoelastosis, skin cancer, and cataracts at these wavelengths. Irradiation exposure that lasts more than 10 years is associated with a sharp increase in the probability of carcinogenesis and cataractogenesis; maximum permissible doses are only 15% of the values presented in Table 7. Aside from doses, the latter instance must account for radiation intensity, which must not exceed the intensity of homogeneous irradiation in the maximum permissible dose.

The standards considered cannot be used in space without being corrected for flight conditions. The modifying effect of flight factors can significantly alter space crew health status as well as the living environment. For example, long-term confinement in a small, closed environment affects both human autoflora and the microflora of the environment. The consequences of these changes against a background of UVR-induced immunosuppression are difficult to predict. The influence of stimulated vitamin D_3 synthesis on calcium metabolism in weightlessness also is unclear. Additional research is needed on the biomedical effects of UVR in combination with other spaceflight factors in order to correct the appropriate standards.

VI. Mechanisms by which Weak EMR Interact with Biological Systems

Several mechanisms have been proposed to explain the complex, occasionally inconsistent effects of weak EMR (in particular at the level of the Earth's MF and especially hypogeomagnetic fields) on biological systems.[139] Some[103] explain the sensitivity of living things to Earth MF in terms of biological systems being "entrained" to function at the same frequencies. Others,[140] in noting a positive correlation between curves for half-time of thiole oxidation in biological compounds and the intensity of magnetic flux at 200 MHz, propose that oxidation of sulfhydryl groups on thiole compounds could be used to mark the effect of the Earth's MF on biological systems. Yet others[141] maintain that weak EMR changes the conformational oscillations through changing polychiral biopolymers, i.e., that magnetic fields impair the symmetry of biopolymers by affecting the L and D isomers of organic molecules. Other possible ways that weak MF might incur biological effects are through affecting the speed of diffusion and orientation of macromolecules with magnetic sensitivity; and the interaction of weak MF with corresponding electric currents and volumetric charges that induce magnetohydrodynamic pressure in cells.

However, Garibov and Ostrovskiy[142] contend that the results described in the published literature may be random, and that reproducible nonthermal effects of EMR on biological macromolecules have yet to be demonstrated. Their analysis covered exposure of organisms to microwave radiation (i.e., wavelengths in the millimeter range). Nor were resonance effects found on the organismal level. These conclusions would seem logical for the Earth's magnetic field as well: If geomagnetic fields have a negligibly weak effect on a biological system (energy is billions of times lower than kT-thermal noise), and various types of biophysical and chemical "tricks" have to be invoked to explain certain phenomena, then explaining the effects of hypogeomagnetic fields would be more difficult still.

How is it that the same "functional disorders" can be generated by either geomagnetic fields or hypogeomagnetic fields? On the Earth's magnetic field is superimposed the more significant EMF of technologically generated origin, and their effects probably disguise the weak biological effects of geomagnetic fields. Studies of the biological effects of weak MF suggest that natural EMF may not be crucial in terms of occupational safety. Safe exposure limits for technologically generated EMF are hundreds or thousands of times higher than for geomagnetic fields. In our opinion, neither geomagnetic nor magnetic fields represent a danger to individuals working in those fields. Space crews will never be "starved" for electromagnetic energy, as they will always be "fed" it by space systems.

VII. Inherent Electromagnetic Fields in Humans: Biomagnetism

The surface of any living thing is a mosaic of weak electrical potentials, created by the electrical activity of the muscles, brain, heart, and nerves; those potentials are in the thousands of volts, and form a field of frequencies ranging from 10^{-2} to 10^{-7} Hz.[41] Humans also possess magnetic fields of intensity ranging from 10^{-13} to 10^{-9} T (0–2000 Hz).[43] These MF have been recorded from adult and fetal hearts, brains (both background and in response to visual, auditory, or somatic stimuli), muscles, and eyes, the latter by magnetooculography and magnetoretinograms.

Interest in the late 1980s has focused on the MF of the heart and brain, with regard to their applications in both diagnosis and occupational health. The intensity of the heart's MF (about 50 pT) is one-millionth of the geomagnetic field. In humans, the MF near the head ranges from 0.01–0.1 pT, and is chiefly alpha waves.[89] The electrostatic field potential for a point 10 cm from the human body surface can reach 2 or 3 V. The mean intensity of the human electric field is 15 ± 2.2 V/m, and can reach 80 V/m in athletes.[143] Recorded oscillations of 10–100 mV (0.005–0.05 Hz) could reflect the function of the gastrointestinal tract.[143] A system that allows the distribution of EF around biological objects (including humans) to be visualized has been reported by Japanese investigators.[42]

Interactions of the intrinsic MF of humans with the external MF of their environments are of practical as well as theoretical interest. The magnetic properties of biological tissues are of interest with regard to how external MF would influence the body. For example, the amplitude of the cardiac T wave increases when the external MF is increased beyond twice that of Earth, and decreases as the external MF decreases to zero. The response to a visual stimulus is different in humans exposed to unusual external MF[43]; also, fluctuations in the human MF have been recorded up to one second before a voluntary movement or spoken word.[43] The latter finding could be useful in assessing the effects of environmental conditions on psychological function.

Magnetic inclusions clearly play significant roles in orientation for bacteria and for birds,[144] although their significance in humans is unclear. Their presence in the skull, particularly around the nose,[145] is thought by some to be linked with the ability to sense external magnetic fields and spatial orientation when input from sensory organs are blocked; however, others[144] consider such a "homing effect" to be an artifact. MF also could influence neurophysiological processes in one of three ways, i.e., through dendro-dendrite conduction, neuron-neuroglial interactions, and perception of weak electric (or perhaps magnetic) fields.[49] Finally, the electromagnetic compatibility of biological systems with their environments might even explain the adverse effects of EMF on vital biological processes; the presence of ferromagnetic inclusions in biological subjects could cast light on general ecological issues of magnetobiology.[43]

Further, the significance of interactions between natural and technological MF and EMF (radioelectronic complexes, life-support systems etc.) with human systems in the hypomagnetic medium of space probably should not be ignored. The biological response of an organism long exposed to hypomagnetic fields and microgravity can be assessed only through spaceflight experiments.

The complex, multifaceted topic of biomagnetic fields has been approached differently by many different investigators. Although physicists tend to deny the physiological role of biological MF, at least one[43] has proposed that biological MF can be sensed by the organism by means of the Josephson effect. On the other hand, another group[146] contends that only MF greater than 200 mT—which is characteristic only of artificial MF—produce biological effects. Further details of the complex subject of biomagnetics can be found in Refs. 43, 144, and in proceedings of biomagnetism conferences held in Boston in 1976, in Grenoble in 1978, in Berlin in 1980, in Rome in 1982, and in Vancouver in 1984.

VIII. Conclusions

The ultimate affirmation—or denial—of the biological significance of any factor can be provided only by detailed epidemiological studies of human subjects. With regard to the potential for harm of any particular factor related to EMR, epidemiological observations are problematic because of the absence of specific, clear clinical symptoms. Moreover, actual exposures to electromagnetic factors typically involve other confounding factors as well, e.g., ionizing radiation. Finally, the biological significance of EMR in free space may differ from EMR aboard the spacecraft or on Earth.

The various types of EMR can be ranked with regard to their biological activity as follows: UVR > microwaves > radiofrequency > electric fields > magnetic fields > geomagnetic fields > hypogeomagnetic fields. This rank-order is determined first by the frequency of radiation, next by the intensity of the EMR, and next by the modulation of the carrier frequency. The intensity of space UVR exceeds that at the surface of Earth by several hundred percent. When space UVR passes through the quartz windows of a spacecraft, it can combine with radiation from artificial sources to form a field that can affect human crew members, their living environment, and biological components of the life-support system. For these reasons, we have focused on EMR in the ultraviolet, microwave, and low-frequency bands.

In our opinion, special limits or standards for the "natural" EMR arising from Earth and from biological objects probably are not needed for space crews, since that EMR resembles that to which humans are regularly exposed on Earth. Similarly, technologically engendered EMR on brief flights in near-Earth space probably does not require special standards either, since existing standards include the use of safety factors not less than 10. However, in the absence of experimental and epidemiological evidence, prudence demands that these statements remain ambiguous, at least until evidence can be obtained to verify that EMR on long flights, especially in combination with other spaceflight factors, is not hazardous to human health and performance.

Selecting organ systems for study, and criteria with which to study them, for cosmonaut EMR exposure is difficult. Studies such as these probably should focus first on the incidence of diseases, ocular damage, biological aging, and genetic effects. The effect of EMR on the health of space crew members cannot be isolated from the WHO "Health for All by the Year 2000" Program. Because diseases of civilization are associated mainly with the cardiovascular, nervous, immune, and metabolic systems, these systems probably should be emphasized in epidemiologic studies of EMR. Individual sensitivity to EMR for space crews should be evaluated in terms of prognostic criteria that themselves are based on integrated health indices such as those described in Refs. 147 and 148.

Future attention should be directed toward the potential benefits of some EMR exposures, which may exceed the risk of harmful effects. Some indications exist for the use of EMR in medicine (e.g., rehabilitating chilled crew members) and for modifying the plant and microbial components of closed life-support systems. Also, ultraviolet light may prove to be useful in compensating for negative effects of weightlessness and hypokinesia in space. Specifically, natural UVR is used by humans to synthesize vitamin D, which regulates calcium metabolism; the general tonic effect of chronic low doses of radiation seem promising as well.

Pilots, space crew members, engineers, and others should have a clear understanding of the boundary between the harmless and harmful effects of EMR. Occupational information about the uses and harm from EM sources is essential. Physicians should take an active interest in eliminating radiophobia in occupational situations, both to improve protection and to expand human potential. In the words of Stefanov,[149] people should be taught not only what they must do to maintain their health, but also what they must do to improve it.

Finally, the ecological aspect of consuming electromagnetic energy deserves consideration as well. The human spaceflight program uses the most power by far of any aspect of space technology, and is thought by some to be the greatest polluter of the environment as well. To paraphrase Ward and Dubois,[150] humans may yet reach the planet Mars, but will do so only from being up to their knees in garbage on Earth.

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